

Light curve solutions of the eccentric *Kepler* binaries KIC 11619964 and KIC 7118545 and mid-eclipse brightening of KIC 11619964 ^{*}

Diana Kjurkchieva¹ and Doroteya Vasileva¹

Department of Physics, University of Shumen, 115 Universitetska Str., Shumen, Bulgaria

d.kyurkchieva@shu-bg.net

(Submitted on; Accepted on)

Abstract. We carried out light curve solutions of two eclipsing detached binaries on eccentric orbits observed by *Kepler*. The orbits and fundamental parameters of KIC 11619964 and KIC 7118545 were determined with a high accuracy by modeling of their photometric data. We found that the temperatures of their components differ by around 2000 K while the radii of their secondaries are more than twice smaller than those of the primaries. We detected a strange "brightening" of KIC 11619964 in the narrow phase range (± 0.0005) around the center of the primary eclipse reaching to 0.018 mag in amplitude. This "mid-eclipse brightening" needs follow-up observations with good time resolution.

Key words: binaries: close – binaries: eclipsing – methods: data analysis – stars: fundamental parameters – stars: individual (KIC 11619964, KIC 7118545)

Introduction

The tidal forces change the stellar shape (tidal bulges) and cause brightness variability due to projection of the distorted stellar surfaces on the visible plane (Brown et al. 2011, Welsh et al. 2011, Morris 1985). It has double-wave shape (ellipsoidal variations) in the case of circular orbits and light increasing around the periastron in the case of eccentric orbits.

Close binaries on eccentric orbits are the main targets for study of the tidal phenomena: mechanisms for circularization of the orbits and synchronization of the stellar rotation with the orbital motion; impermanent mass transfer occurring close to the periastron (Sepinsky et al. 2007a, Lajoie & Sills 2011); tidally excited brightening and oscillations (Kumar et al. 1995, Handler et al. 2002, Maceroni et al. 2009). The theoretical studies revealed that binaries could remain on eccentric orbits for long periods of time. Hence, the binary stars on eccentric orbits have also important evolutionary role (Sepinsky et al. 2007b, 2009).

The eclipsing eccentric binaries (EEBs) with an apsidal motion provide valuable observational tests of the theoretical models of stellar structure and evolution (Kopal 1978, Claret & Gimenez 1993, Willems & Claret 2005). These stellar systems are important objects for the modern astrophysics but their study is straitened due to the long periods. Recently the huge surveys as ROTSE, MACHO, ASAS, SuperWASP, covering large part of the whole sky, increased considerably the number of EEBs. However, the huge contribution to their study belongs to the space missions, especially *Kepler* (Koch et al. 2010), covering small sky area, but providing high-accuracy data. The unprecedented *Kepler* observations allowed to discover and investigate a new tidally excited effect, called "heartbeat" phenomenon (Welsh et al. 2011, Thompson et al. 2012, Kjurkchieva & Vasileva 2015).

^{*} based on data from the *Kepler* mission

Several thousands eclipsing detached systems, considerable part of them on eccentric orbits, were discovered by *Kepler* (Prsa et al. 2011). The rich and valuable resources of the *Kepler* database are available for additional research.

The goal of this study is determination of the orbits and physical parameters of two eccentric binaries, KIC 11619964 and KIC 7118545. They have relatively long eclipses (above 0.01 in phase units) and allow precise light curve solutions. Table 1 presents available information for these targets (Prsa et al. 2011, Slawson et al. 2011): orbital period P ; *Kepler* magnitude m_K ; mean temperature T_m ; width of the primary eclipse w_1 (in phase units); width of the secondary eclipse w_2 (in phase units); depth of the primary eclipse d_1 (in flux units); depth of the secondary eclipse d_2 (in flux units); the phases φ_2 of their secondary eclipses (the phases φ_1 of the primary eclipses are 0.0).

Table 1. Parameters of the targets from the EB catalog

Kepler ID	P	m_K	T_m	w_1	w_2	d_1	d_2	φ_2
11619964	10.3685	14.545	5582	0.015	0.014	0.136	0.035	0.456
7118545	14.7972	14.185	6095	0.019	0.014	0.251	0.029	0.675

Light curve solutions

The modeling of the *Kepler* data was carried out by the package *PHOEBE* (Prsa & Zwitter 2005). The out-of-eclipse parts of the observed light curves of the two targets are almost constant and we used for modeling the mode "Detached binaries".

We calculated preliminary values of the eccentricity e and periastron angle ω by the formulae (Kjurkchieva & Vasileva 2015)

$$e_0 \cos \omega_0 = \frac{\pi}{2} [(\varphi_2 - \varphi_1) - 0.5] \quad (1)$$

$$e_0 \sin \omega_0 = \frac{w_2 - w_1}{w_2 + w_1}, \quad (2)$$

which are approximations of the formulae of Kopal (1978). The obtained values of e_0 and ω_0 were used as input parameters of *PHOEBE*.

The mean temperatures T_m of our targets (Table 1) required to adopt coefficients of gravity brightening 0.32 and reflection effect 0.5 (appropriate for stars with convective envelopes). We used linear limb-darkening law with limb-darkening coefficients corresponding to the stellar temperatures and *Kepler* photometric system (Claret & Bloemen 2011).

We used for modeling 5000 points from the quarters Q1 and Q2 for each target and the period values from Table 1.

The procedure of the light curve solutions was carried out in several stages. Initially the primary temperature T_1 was fixed to be equal to the mean target

temperature T_m (Table 1). We input some guessed values of the secondary temperature T_2 , mass ratio q , orbital inclination i and potentials $\Omega_{1,2}$ (appropriate for detached systems) and varied only the eccentricity e and periastron angle ω around their input values e_0 and ω_0 to search for the best fit of the phases of the eclipses (estimated by the value of χ^2).

At the second stage we fixed e and ω and varied simultaneously T_2 , q , i and $\Omega_{1,2}$ (and thus relative radii $r_{1,2}$) to search for the best fit of the whole light curves.

Table 2. The derived orbital parameters of the targets

Kepler ID	e	ω [deg]	φ_{per}
KIC 11619964	0.0891 ± 0.0001	223.45 ± 0.01	0.348
KIC 7118545	0.3137 ± 0.0001	332.04 ± 0.01	0.769

Table 3. Parameters of the best light curve solutions

Kepler ID	i	q	T_1	T_2	r_1	r_2	l_1	l_2/l_1
11619964	88.306	0.602	5877	4177	0.0419	0.0187	0.950	0.0526
	± 0.003	± 0.002	± 26	± 10	± 0.0002	± 0.0001		
7118545	89.531	0.507	6154	3936	0.0408	0.0202	0.959	0.0427
	± 0.001	± 0.001	± 12	± 3	± 0.0002	± 0.0003		

Further, we used the obtained values T_2 (and correspondingly $\Delta T = T_m - T_2$) and $c = l_2/l_1$ (l_2 and l_1 are relative stellar luminosities from the second stage of the solution) to calculate the next approximations of T_1^m and T_2^m

$$T_1^m = T_m + \frac{c\Delta T}{c+1} \quad (3)$$

$$T_2^m = T_1^m - \Delta T \quad (4)$$

which are yet on the two sides of the mean value T_m of the target.

Finally, we input the parameter values from the second stage and the new temperature values T_1^m and T_2^m and varied all parameters in small ranges around these values until reaching the best fit to the observations (minimum of χ^2). The final parameters of the eccentric orbits are given in Table 2 while Table 3 contains the parameters of the stellar configurations. The synthetic curves corresponding to the parameters of our light curve solutions are shown in Figs. 1-2 as continuous lines.

The parameter errors in Tables 2–3 are the formal *PHOEBE* errors. Their small values are natural consequence of the high precision of the *Kepler* data.

The synthetic curves reproduced very well the *Kepler* data. The residual curves show some bigger discrepancies during the eclipse phases (Figs. 1–2). Similar behavior could be seen also for other *Kepler* binaries (Hambleton et al. 2013, Lehmann et al. 2013, Maceroni et al. 2014), especially those with small sum of relative radii. It was attributed to the effects of finite integration time (29.42 minutes for the *Kepler* long-cadence data) studied by Kipping (2010).

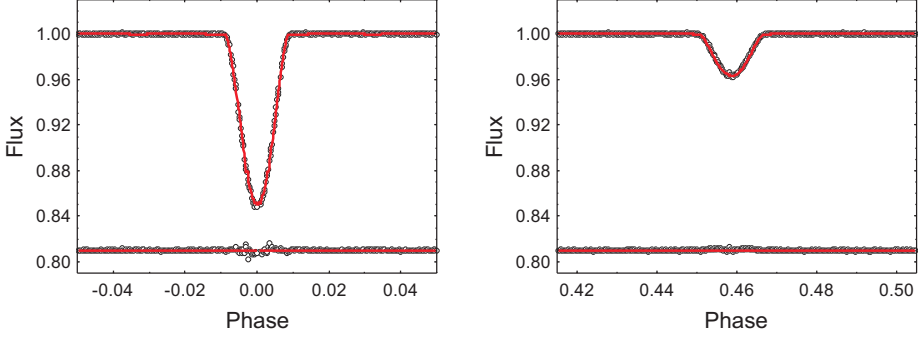


Fig. 1. The primary (left panel) and secondary (right panel) eclipse of KIC 11619964 and their fits

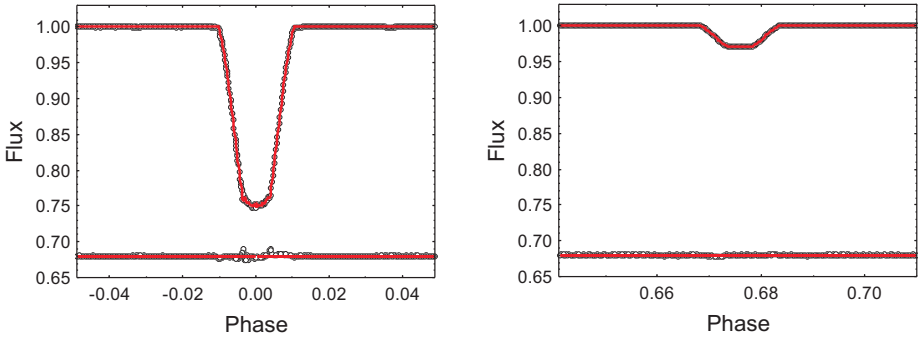


Fig. 2. The primary (left panel) and secondary (right panel) eclipse of KIC 7118545 and their fits

Analysis of the results

The analysis of our light curve solutions of KIC 11619964 and KIC 7118545 led to several conclusions.

(1) The temperatures of stellar components are in the range 3930–6150 K. The primaries are the hotter components. The temperatures of the secondaries are smaller with about 2000 K than those of the primaries. This result is natural consequence of the shallow secondary eclipses of the two targets.

(2) The orbital inclinations of the targets are near to 90° (Table 3) that is expected for eclipsing systems with periods above 10 days. KIC 7118545 undergoes total eclipse.

(3) The stellar radii of the secondaries of the two targets are more than twice smaller than those of the primaries. This result together with their considerably lower temperatures lead to the very small luminosity ratio l_2/l_1 for the two eccentric binaries (0.043–0.053).

(4) The mass ratios of the targets are within the range 0.5–0.6.

(5) We did not find evidences for apsidal motion of our targets. The possible reason is the relative short duration of the *Kepler* observations. Typically apsidal periods are at least decade long (Michalska & Pigulski 2005). Moreover, the systems with apsidal motions are with the shortest orbital periods or with the largest sum of relative radii for a given eccentricity (Michalska 2007) but these conditions are not fulfilled for our targets.

(6) The review of the light curves of our targets from different quarters did not exhibit any long-term variability.

(7) The out-of-eclipse light of the targets is constant within 0.15 %.

Table 4. Comparison of our results with those of automated fitting

Kepler ID	T_2/T_1	$r_1 + r_2$	$\sin i$	source
KIC 11619964	0.875	0.098	0.99486	Slawson et al. 2011
	0.711	0.0606	0.99956	our
KIC 7118545	0.823	0.086	0.99855	Slawson et al. 2011
	0.640	0.0610	0.99997	our

(8) Table 4 presents the values of the temperature ratio T_2/T_1 , sum of the relative radii $r_1 + r_2$ and $\sin i$ of our "manual" light curve solutions and those determined by a neural network analysis (automated modeling) of the phased light curves of our targets (Prsa et al. 2011, Slawson et al. 2011). The last method does not provide error values but gives statistical parameter uncertainties. Slawson et al. (2011) estimated that 90% of the sample of detached and semi-detached EBs had a corresponding error in T_2/T_1 , $r_1 + r_2$ and $\sin i$ smaller than 10 %. However, our solutions do not confirm this estimation, particularly for KIC 11619964 and KIC 7118545.

(9) We found a strange "brightening" (Fig. 3) of KIC 11619964 in the narrow phase range 0.0005 around the center of the primary eclipse reaching to 0.018 mag in amplitude (these points were excluded from the procedure of

modeling). Unfortunately, there are not short-cadence data of KIC 11619964 (with good time resolution) and we are not able to analyze the observed effect in details.

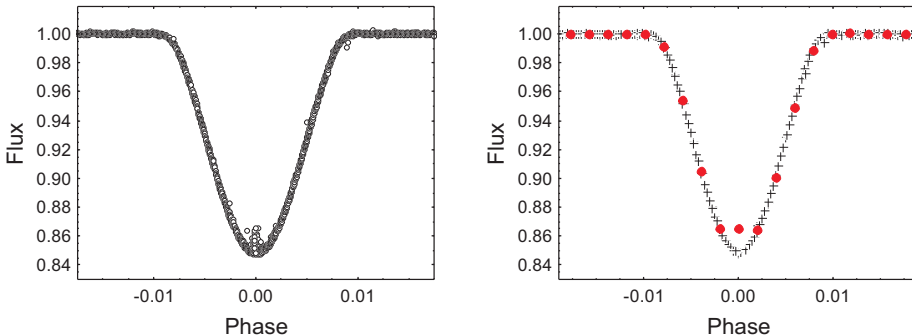


Fig. 3. Left panel: The "brightening" at the primary eclipse of KIC 11619964 (all 65000 points available in the *Kepler* archive are used); Right panel: primary eclipse with brightening (red circle symbols) superposed on several normal ones (black pluses)

The detected mid-eclipse brightening could be attributed to: (i) artificial effect of the *Kepler* observations or automated reducing or de-trending of the data of the *Kepler* archive (but why only for this target?); (ii) some peculiarity of KIC 11619964. Similar effect has been established for the primary or secondary eclipse of other detached, semidetached, contact and overcontact binaries (see table in Snyder & Lapham 2008). Their mid-eclipse brightenings also do not occur at every eclipse (Pribulla 1999) and have variable amplitude. The amplitudes of four of the detached systems in the table of Snyder & Lapham (2008) are 0.002–0.04 mag, only that of ϵ Aur is considerably bigger. The phenomenon of mid-eclipse brightening has not any plausible explanation yet (Snyder & Lapham 2008).

Estimation of the global parameters

Due to the lack of radial velocity measurements we estimated the global parameters of the target components by the following procedure.

The primary luminosity L_1 was determined by the relation "temperature, luminosity" for MS stars while the secondary luminosity was calculated by the formula $L_2 = (l_2/l_1)L_1$ where the luminosity ratio l_2/l_1 is derived from the light curve solution (Table 3).

The orbital separation a in solar radii was obtained from the equation

$$\log a = 0.5 \log L_i - \log r_i - 2 \log T_i + 2 \log T_{\odot}, \quad (5)$$

where the relative radii r_i and temperatures T_i were taken from the light curve solution (Table 3). Then the absolute radii were calculated by $R_i = ar_i$.

The total mass M (in solar units) was calculated from the third Kepler law

$$M = \frac{0.0134a^3}{P^2}, \quad (6)$$

where the orbital period P was in days while the orbital separation a was in solar radii. Then the individual masses M_i were determined from the formulae $M_1 = M/(1 + q)$ and $M_2 = M - M_1$.

Table 5. Global parameters of the target (in solar units)

Kepler ID	M_1	M_2	R_1	R_2	L_1	L_2
11619964	1.25 ± 0.09	0.75 ± 0.05	1.05 ± 0.03	0.47 ± 0.01	1.11 ± 0.03	0.058 ± 0.004
7118545	0.74 ± 0.03	0.37 ± 0.01	1.07 ± 0.02	0.53 ± 0.01	1.49 ± 0.01	0.064 ± 0.004

Conclusions

This paper presents the results of determination of the orbits and fundamental parameters of the eclipsing eccentric binaries KIC 11619964 and KIC 7118545 on the basis of their *Kepler* data. The results could be used to improve the empirical relations between the stellar parameters as well as to investigate the tidal induced effects.

KIC 11619964 deserves follow-up photometric observations, especially at the primary minimum, with good time resolution to study its mid-eclipse brightening effect.

Acknowledgments

The research was supported partly by funds of project RD-08-285 of Scientific Foundation of Shumen University. It used the SIMBAD database and NASA Astrophysics Data System Abstract Service. We worked with the live version of the *Kepler* EB catalog (<http://keplerebs.villanova.edu/>). The authors are grateful to the anonymous referee for the useful notes and propositions.

References

- Brown W., Kilic M., Hermes J., et al., 2011, ApJ, 737, L23
- Claret A., Bloemen S., 2011, A & A, 529A, 75
- Claret A., Gimenez A., 1993, A & A, 277, 487
- Hambleton M., Kurtz W., Prsa A., et al., 2013, MNRAS, 434, 925
- Handler G., Balona A., Shobbrook R., et al., 2002, MNRAS, 333, 262
- Kipping M., 2010, MNRAS, 408, 1758
- Kjurkchieva D., Vasileva D., 2015, PASA, 32, 23

- Koch G., Borucki J., Rowe F., et al., 2010, *ApJ*, 713, L79
Kopal Z., 1978, *ASSL (Astrophysics and Space Science Library)* 68, Dordrecht, D. Reidel Publishing Co.
Kumar P., Ao C., Quataert E., 1995, *ApJ* 449, 294
Lajoie C., Sills A., 2011, *ApJ*, 726, 67
Lehmann H., Southworth J., Tkachenko A., et al., 2013, *A & A*, 557A, 79
Maceroni C., Montalb n J., Michel E., et al., 2009, *A & A*, 508, 1375
Maceroni C., Lehmann H., da Silva R., et al., 2014, *A & A*, 563A, 59
Michalska G., Pigulski A., 2005, *A & A*, 434, 89
Michalska G., 2007, *IBVS*, 5759
Morris, S. L. 1985, *ApJ*, 295, 143
Pribulla T., 1999, *A & A*, 345, 137
Prsa A., Zwitter T., 2005, *ApJ* 628, 426
Prsa A., Batalha N., Slawson W., et al., 2011, *AJ* 141, 83
Sepinsky J.F., Willems B., Kalogera V. 2007a, *ApJ*, 660, 1624
Sepinsky J.F., Willems B., Kalogera V., et al., 2007b, *ApJ*, 667, 1170
Sepinsky J.F., Willems B., Kalogera V., et al., 2009, *ApJ*, 702, 1387
Snyder F., Lapham J., 2008, *SASS*, 27, 29
Thompson E., Everett M., Mullally F., et al., 2012, *ApJ*, 753, 86
Welsh W., Orosz A., Aerts C., et al., 2011, *ApJS*, 197, 4
Willems B., Claret A., 2005, *SPC*, 333, 52